THE LEARNING CURVE AND ITS APPLICABILITY TO NAVY AIRCRAFT OVERHAUL PROGRAMS

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Since World War II, industrial management has been undergoing a transition from an art, based on experience, towards a profession, based on a structure of principles and science. The cause of this transition is the need for a systematic understanding of the forces that comprise the dynamic character of industrial effort. One of the techniques that is evolving in this transitory period is the learning curve theory. This theory has the unique ability to predict, with a high degree of accuracy, future declines in man-hour requirements to accomplish work of a repetitive nature. The airframe industry has accepted this technique as a principal component of its management decision making process. As a tool to enhance effective management, it is believed it has applicability to most Navy production and overhaul programs. Its applicability to three aircraft overhaul programs is established by an analysis of empirical data gathered from a major Naval air station. Aggressive management, in this age of rapid change, cannot afford to overlook any advance that will clarify and fortify decisions based on experience, intuition, and judgment.

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Preface

An executive of a washing machine firm chanced to cross paths with an executive of a large aircraft firm. The conversation turned to manufacturing costs and the appliance executive remarked, "It has taken my company two years to determine the exact cost of the current washing machine we are manufacturing."

The aircraft executive stated that many times his company is forced to make cost determinations on similar items within a matter of a few minutes. Then he said, "I'll bet you a steak dinner that I can calculate the cost of your 100,000th washing machine within 10% accuracy by using a learning curve based on aircraft production."

The appliance executive accepted the bet and in response to questions he furnished the weight of the washing machine and the cost of the first unit produced. During the next few minutes he watched the aircraft executive work with pencil, ruler, and log-log graph paper.

After he had completed plotting the curve, the aircraft executive stated, "Your 100,000th washing machine should cost you $134.80."

"Just drop the 80 cents," the appliance executive said. "It was actually $134.00."

CHAPTER I

LEARNING CURVES AND THEIR USES

The Preface of this study may have the sound of a fairy tale but actually it contains more fact than fiction. The technique that the aircraft executive was using is known by many names: learning curve, improvement curve, progress curve, management improvement curve, and efficiency curve. Regardless of the specific name applied, the technique does have unique predictive abilities that may preclude management decision based on the hunch or guesstimate.

A. LEARNING CURVE THEORY

There is no general body of literature that covers the application of the learning curve theory to general manufacturing and rework of a repetitive nature. Much has been written concerning its use in the airframe industry. In fact, from the manufacturing standpoint, it was the airframe industry that prior to World War II developed the technique and used it for estimating the cost of producing airframes.[1]

[1]Harold Asher, Cost-Quantity Relationships in the Airframe Industry (U.S. Air Force Project Rand, RAND Corporation, Santa Monica, California, July 1956) R-291 p. 1.

Basically, the learning curve is simple to understand. Intuitively it has been accepted by mankind for centuries i.e., a worker learns as he works. The more frequently a worker repeats an operation, the more efficient he becomes. The more efficient he becomes, the less labor that is involved in the units produced. This idea is not new but what is relatively new is that the efficiency or improvement is regular enough to be predictable. This predictability is what has revitalized an otherwise commonplace notion and affords industry a new tool to be used in the solution of its many and complex problems.

As far as can be determined, this predictability was first discovered in 1936 by T. P. Wright of the Curtiss-Wright Corporation.[2] From empirical studies he found that the relationship between average direct man-hour cost and cumulative number of airframes produced (cumulative output) could be expressed by the function

$$\overline{Y} = ax^b,$$

where $\overline{Y}$ is average direct man-hours, x is cumulative output, and a and b are parameters. The value of a yields the direct man-hour cost

[2] T. P. Wright, "Factors Affecting the Cost of Airplanes," Journal of the Aeronautical Sciences, Vol. 3, February, 1936, pp. 122-128.

for unit number one and the value of b defines the "slope" of the progress curve. From his studies Wright found that b had a value of -.322. In Wright's formula this value for b produces an "80 per cent" curve. This means that each time the total quantity of units produced is doubled, average man-hour cost declines to 80 per cent of the average cost before the doubling of output. In general terms, the learning curve theory states that as the total quantity of units produced doubles, the cost per unit declines by some constant percentage.[3]

The learning curve is a product of all efforts to improve. In addition to improvements in worker's methods, a learning curve is affected by better planning on the part of the shop foreman, improvements of tools, simplification of work flow, improved procurement procedures, etc. The most significant of these is increased efficiency on the part of the direct worker. Consequently, the higher the percentage of worker effort versus machine effort, the greater should be the rate of improvement. In the production of screws by automatic screw machines, there is very little room for improvement in the process. On the other hand, considerable improvement is experienced when a person puts a jigsaw puzzle together for the second time. It is the totality of manual and mental effort in this second operation

[3]Asher, loc. cit.

that makes the difference.

Another factor that affects a learning curve is previous experience or know-how. If a new design aircraft is to be made by two manufacturers and one of them is new to the industry, it can be expected that this new entry will display a greater absolute reduction in man-hour costs from unit one to two than will be true of the manufacturer with know-how. The latter company will bring its experience to bear on the first unit of production and consequently will require fewer man-hours than the new company who will be gaining experience on its first unit. This difference in starting points does not in inself infer differing learning curves. However, since there is more for the new company to "learn", due to its lack of know-how, the experience gained by it on the first unit will be reflected by a greater reduction in man-hour costs on unit two than that obtained by the manufacturer with previous experience.

B. AIRFRAME INDUSTRY EXPERIENCE

By the end of World War II the U. S. Air Corps was convinced that much could be gained by both the airframe industry and the government if more detailed studies could be made of the learning curve. To further this aim they published, in 1947, the now famous, "Source Book of World War II Basic Date: Airframe Industry".[4] To

[4]Air Material Command, Dayton, Ohio, 1947.

this date this book has been the chief source of data for most empirical learning curve studies. Studies based on these data have been made by all of the major airframe companies, educational institutions, and research companies such as the Stanford Research Institute and the Rand Corporation.

The results of these studies indicate that the learning curves experienced by the industry for World War II fighter production, range from a low of 65 per cent to a high of 95 per cent. Part of the reasoning for this variance is:

> Proven or similar models produced in experienced facilities.
>
> Proven models produced in new facilities.
>
> New models produced in new or experienced facilities.[5]

In order to arrive at a comparative basis for different models, the industry uses as its measurement, man-hour cost per pound of airframe weight.

As a result of these studies the theory has been refined and expanded. Today it is used not only for predicting man-hour cost

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[5] Crawford-Strauss Study, Air Material Command, Dayton, Ohio, 1947, p. 13.

(which is by far the biggest cost factor in airframe production), but also for predicting material and overhead costs. Learning curves are important tools to both the airframe industry and the Government as is evidenced by the following that was reported by W. A. Raberg, Jr., of Northrop Aircraft:

> (1) Military planners use the learning curve to estimate the nation's aircraft mobilization expansion potential. Air Force equipment, pilots, ground crews and supporting personnel, training schools, etc., are all closely coordinated with aircraft production, and therefore reflect the reliability of the learning curve theory;
> (2) The Government uses the learning curve to measure aircraft manufacture for efficiency and production dependability;
> (3) The Government checks aircraft manufacturers' bids for accuracy and reasonableness. This examination is largely based upon statistical analysis of the manufacturer's own record with respect to general industry production performance;
> (4) Aircraft manufacturers use the learning curve in preparing bids for new business;
> (5) Aircraft manufacturers use the learning curve in developing labor loads, area and equipment requirements, shop efficiency measures, budgets, and often standards; and
> (6) Aircraft manufacturers use the learning curve to measure the progress of active contracts. This is often the basis for contract payments and loans.[6]

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[6]W. A. Raborg, Jr., "Mechanics of the Learning Curve," Aero Digest, Vol. 65, No. 5, November, 1952, p. 18.

One of the extraordinary phenomenon concerning the "80 per cent" curve of the airframe industry, that was developed by T. P. Wright in 1936, is the fact that despite the radical changes and technological advances that have taken place in the industry since that time, the current average rate of improvement for all airframes manufactured is still 20% or an 80% learning curve.[7]

C. PURPOSE OF THE STUDY

One of the many responsibilities of the Bureau of Naval Weapons (BuWeps), is the preparation of overhaul schedules for Naval aircraft. As can well be imagined, with a multiplicity of overhaul points, aircraft (including models and configurations), and world-wide locations of aircraft requiring overhaul, the determination of optimal schedules is highly complex and almost impossible to achieve.

It is a well known fact that the results attained from any well structured schedule are only as good as the quality of the information used to develop the results. In computer language, where a well programmed computer represents a highly sophisticated model structure, the term used to connote this output quality is "GIGO" - garbage in, garbage out! Therefore, having settled on an acceptable

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[7] Bureau of Aeronautics Statistical Analysis Course. A course prepared by Harbridge House, Inc., Cambridge, Mass.

model for a schedule, the most important function is the assimilation of reasonably correct and meaningful input information.

The information required to develop an overhaul schedule for the maintenance of Naval aircraft is varied and voluminous. One of the key components of this information is the average time to accomplish the overhaul of the various aircraft models and configurations. This average time is not only important to over-all scheduling but is also important because of its implication in management decisions concerning:

Equipment requirements,

Manning levels,

Budgeting,

Induction of work units,

Work flow,

Production control,

Inventory levels, etc.

Since World War II, learning curves have been widely used by airframe manufacturers to estimate costs and to schedule production. They are accepted by the Department of Defense as one of the elements in pricing airframe procurement contracts. Due to the success of learning curves in this sector of industry, it is believed

that the same technique may have application in overhaul or re-work programs.

Consequently, the primary purpose of this study is to determine whether or not there is applicability of the learning curve theory to Navy aircraft overhaul programs. As a secondary purpose, this study will investigate theoretical and empirically deduced implications of the learning curve as a management decision making device.

D. DEVELOPMENT OF A LEARNING CURVE

1. GENERAL. As stated earlier, a very little has been written about the construction and application of learning curves. What has been written has almost exclusively been in the area of airframe production. Some of these writers have been accused of writing for their fellow specialists in a form that is unintelligible to the average reader and on certain occasions these sophomoric writers even have difficulty understanding each other.[8] The presentation in this study will be in a comprehensible form with only a minimum lacing of mathematical models and derivations.

Perhaps because of the lack of a general body of literature on

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[8] I. D. J. Bross, Design for Decision (New York, The Macmillan Company, 1953), pp. 2-3.

the subject, many people are misinformed as to the use of learning curves. Some people look upon them as panaceas for cost estimation, workload schedules, etc. On the other end of the continium, they are regarded by skeptics as highly theoretical techniques requiring detailed knowledge of higher mathematics and having little or no practical value in arriving at management decisions.

Neither of these extremes is correct. Learning curves, like any other quantitative approach to decision making should never be taken as absolute. Any statement made about a universe when only sample data are at hand is only an inference or implication. However it is often the implications of certain facts rather than the facts themselves that lead to action. So it is with learning curves, predictions are being made on the basis of sample data and as such cannot be accepted as absolute. As a useful tool however, they are better than "guesstimates" and in the airframe industry have proven more valid than previously used techniques.

2. CONSTRUCTING THE CURVE ON ARITHMATIC SCALE PAPER. For illustration purposes, hypothetical data will be used to construct an 80% learning curve. The data in Table I indicates that as the quantities of output are doubled the average man-hour cost declines to 80% of the average cost before the doubling. By plotting these data on arithmatic scale paper, using the horizontal or X axis to

represent the units of production and the vertical or Y axis to represent the average man-hour cost, and connecting the plotted points, a graphic presentation of the curve is available. The resulting curve is shown in Figure I. The dramatic reduction of man-hour costs for the first eight units is quite obvious. The curve then begins to slope downward more gradually as the percentage of improvement is spread over a larger and larger number of units.

The sharp reduction experienced in the first units reflects the early correction of problems that were either not resolved or were overlooked in initial planning and tooling.[9]

TABLE I

HYPOTHETICAL DATA OF AN 80 PER CENT LEARNING CURVE

UNIT	CUMULATIVE AVE. MAN-HOURS
1	10,000
2	8,000
4	6,400
8	5,120
16	4,096
32	3,277
64	2,621

[9]Careful planning and efficient tooling usually are reflected in lower first unit costs and since there is less for the workers to "learn" during production, results in a decrease in the slope of the curve.

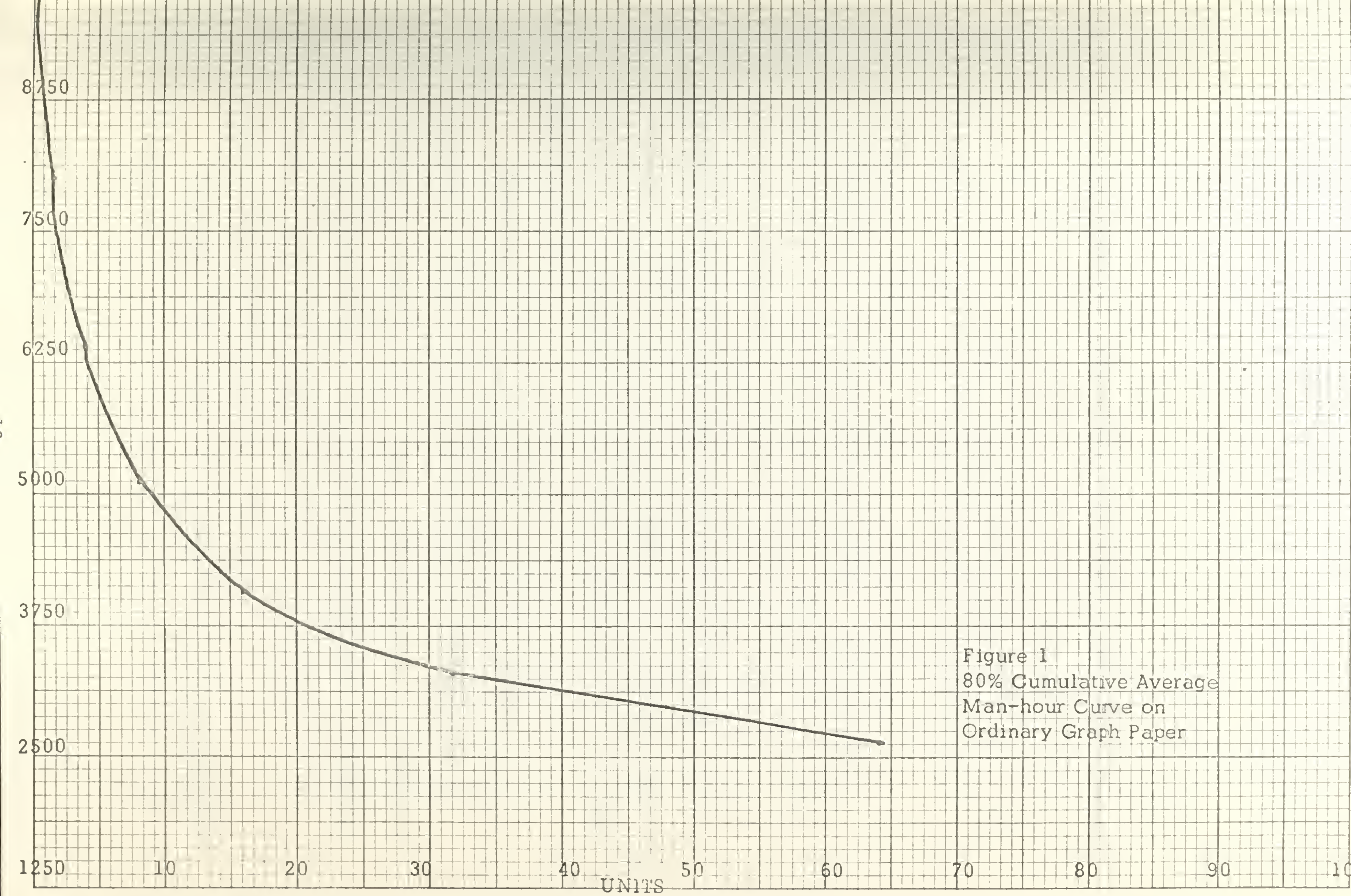

Figure 1
80% Cumulative Average
Man-hour Curve on
Ordinary Graph Paper

The main disadvantage of plotting the curve on arithmatic scale paper is that it is difficult at first glance to detect the linearity of the percentage improvement (80% between doubled quantities). Additionally, when the number of units is large, the arithmatic scale is inconvenient because of the space required to plot the data. To overcome these and other reasons the learning curve is usually plotted on log-log paper.

3. THE LEARNING CURVE ON LOG-LOG PAPER. Log-log paper is simply a grid that uses a ratio scale on the horizontal and vertical axis. The fundamental property of a ratio scale is that a given distance on a particular scale always represents the same ratio or the same per cent difference--no matter where on the scale this distance is taken. The distance from 1 to 2 equals that from 2 to 4, and that from 4 to 8, etc.

When the same data from Table I are plotted on log-log paper, as shown in Figure 2, it is to be noted that the learning curve is portrayed by a straight line. This is in keeping with the linearity of the learning curve theory, that dictates a constant rate of change as quantities are doubled, and the fact that on log-log paper the distance between doubled quantities is also equal.

To determine the slope of a plotted curve, it is first necessary to reproduce the curve so that the unit number one intercept on the

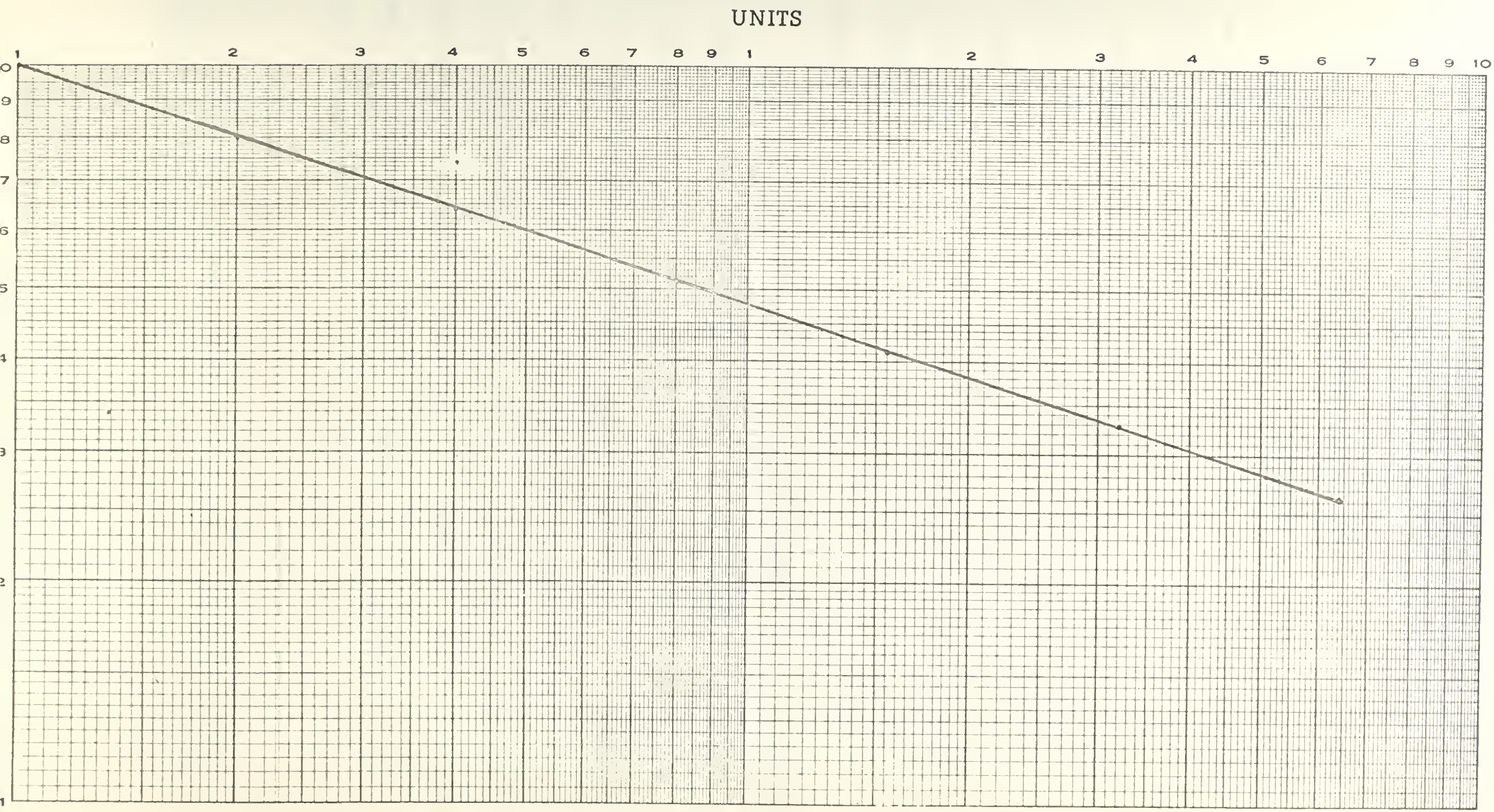

Figure 2
80% Cumulative Average Man-hour
Curve on Logrithmic Paper

vertical or Y axis coincides with the last reference number in the cycle in which the data are contained. (This new plot may also be considered as the first reference number of the next higher cycle.)[10] In the case of Figure 2 the unit number one data intercepts the Y axis at the last reference number of the cycle, 100, therefore the slope of the curve to unit number two and the point at which this bisects the Y axis indicates the slope of the curve. Realizing that the data used to construct the curve in Figure 2 was drawn from hypothetical data representing an 80% curve (Table I), it is not by coincidence that the determination resulted in an 80% curve.

Figure 3 is a typical learning curve to illustrate how this method is used when the value of unit number one intercepts the Y axis at other than the end of a cycle. The easiest way of reproducing the curve, so that the unit number one intercept on the Y axis coincides with the last reference number in the cycle, is through the use of a set of parallel rulers. Lacking these, it is necessary to measure the distance from where the plotted curve intercepts the Y axis-unit number one- to the end of the cycle. In Figure 3 this distance is 5/8". Then, at any second point on the plotted curve, the same distance is

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[10]On the log-log paper, one cycle spans a 10 to 1 ratio; that is, the number at the top of a cycle is 10 times the number at the bottom of the cycle. The number of cycles to be used on the vertical and horizontal depends on the magnitude of the data to be plotted.

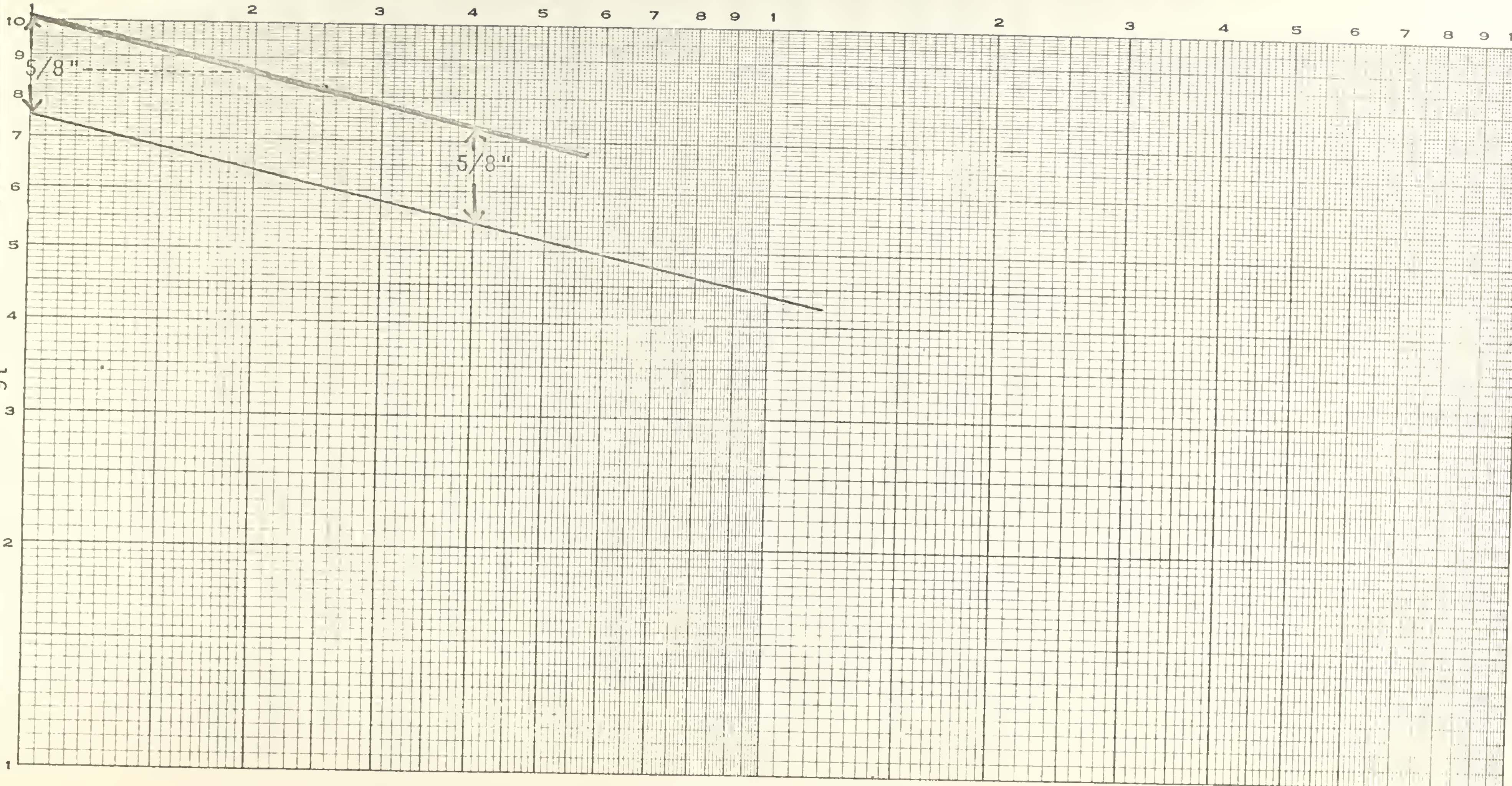

Figure 3
Determining % Applicable to a Learning Curve (Data Plotted Through 13th Unit)

measured off vertically. In Figure 3 this was arbitrarily done at unit number four. This second point is then connected to the point of the end of the cycle by a straight line. Of course, this line will be parallel with the plotted curve. The point at which this line bisects the Y axis for unit number two indicates the slope of the curve. In this case the curve is approximately 85%.

Another method of accomplishing the same thing is to select any point on the learning curve. Select another point at twice the production of the first unit. Divide the labor hours of the second unit by the labor hours of the first unit. Assuming the first point picked is 10 units then the second point would be 20 units. Then, labor hours of the 20th unit divided by the labor hours of the 10th unit equals the learning curve percentage.

A logarithmic solution is explained in the next section.

4. SMOOTHING OUT A LEARNING CURVE. In constructing a cumulative average man-hour learning curve, it is first necessary to accumulate the cumulative average man-hour data and then plot the data on log-log paper. It would be sheer coincidence if this plotting resulted in a recognizable straight line. In almost every case a straight line will have to be fitted. This fit can be done by inspection if the plotted points are reasonably close to a hand fitted line. If the points are not reasonably close to the fitted line, then the

determination of the best fitted line will have to be achieved mathematically.

There are many methods for accomplishing this fit mathematically. One method, developed by the Boeing Airplane Company, is especially designed for a log-log relationship.[11] This method is rather lengthy and complex and will not be covered here. Probably the best known method for fitting a line to data that evidences linearity is the method of least-squares. This technique was introduced by the French mathematician, Adrien Legendre, more than 150 years ago.[12]

There are three formulae to be used with this method. One is the log of both sides of the formula developed by T. P. Wright to define the slope of the function:

(1) $\text{Log } y = \log a + b \log x.$[13]

There are two others as follow:

(2) $$b = \frac{n \sum \log x \log y - \sum \log x \sum \log y}{n \sum (\log x)^2 - (\sum \log x)^2}$$

(3) $$\log a = \frac{\sum \log y - b \sum \log x}{n}$$

The "n" refers to the number of observations or cumulative averages

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[11] "The Improvement Curve Trainees Manual")Wichita: The Boeing Airplane Company, 1958), pp. 42-43. (Mimeographed.)

[12] A detailed explanation of the method of least-squares can be found in almost every standard textbook on statistics.

[13] For a definition of terms, see page 2.

contained in the data to be smoothed. The b and log a in equations (2) and (3) are the constants in equation (1). The value of b defines the slope of the curve and the value of log a identifies the man-hours that apply to unit number one of the fitted line.

Table II gives sample cumulative average man-hour data for the first ten units of a hypothetical production run. The Table also contains the various preliminary calculations necessary to solve the least-square formulae. In actual practice raw data would be compiled from production or cost accounting records and serve as the basis for these calculations.

TABLE II

CUMULATIVE AVERAGE MAN-HOURS (y) FOR UNITS 1 THROUGH 10 LEAST-SQUARES WORK SHEET

Unit x	y	Log x	$(\text{Log } x)^2$	Log y	Log x Log y
1	8700	.0000	.0000	3.9395	.0000
2	6200	.3010	.0960	3.7924	1.1415
3	5400	.4771	.2275	3.7324	1.7807
4	5100	.6021	.3614	3.7076	2.2323
5	5000	.6990	.4886	3.6990	2.5856
6	4800	.7782	.6053	3.6812	2.8647
7	4500	.8451	.7141	3.6532	3.1873
8	4200	.9031	.8155	3.6232	3.2721
9	4000	.9542	.9102	3.6021	3.4371
10	3800	1.0000	1.0000	3.5798	3.5798
		6.5598	5.2186	37.0104	24.0811

Having completed the work sheet it is next necessary to solve equation (2) for b.

$$b = \frac{10(24.0811) - 6.5598(37.0104)}{10(5.2186) - (6.5598)^2}$$

$$= \frac{240.8110 - 242.7808}{52.1860 - 43.0310}$$

$$= \frac{-1.9698}{9.1550}$$

$$b = -.2152$$

Using this derived value for b, it is now possible to solve equation (3) for log a.

$$\log a = \frac{37.0104 - (-.2152)(6.5598)}{10}$$

$$= \frac{37.0104 + 1.4117}{10}$$

log a = 3.8422, antilog 3.8422 = 6953.

Substituting the determined values of b and log a in formula (1), it is possible to solve for the value of y for any given x. Knowing that the antilog of log a (6953) is the first point on the fitted line, it is only necessary to determine one other point in order to plot the line. Solving formula (1) for y when x equals 6 yields a value of y of 4621. Connecting these two points by a straight line achieves the least-squares fit. Figure 4 illustrates the plotted data from Table II and the fitted curve.

Formula (1) may also be used to determine the per cent of the curve. By letting a equal 100 and x equal 2, the answer for y will be

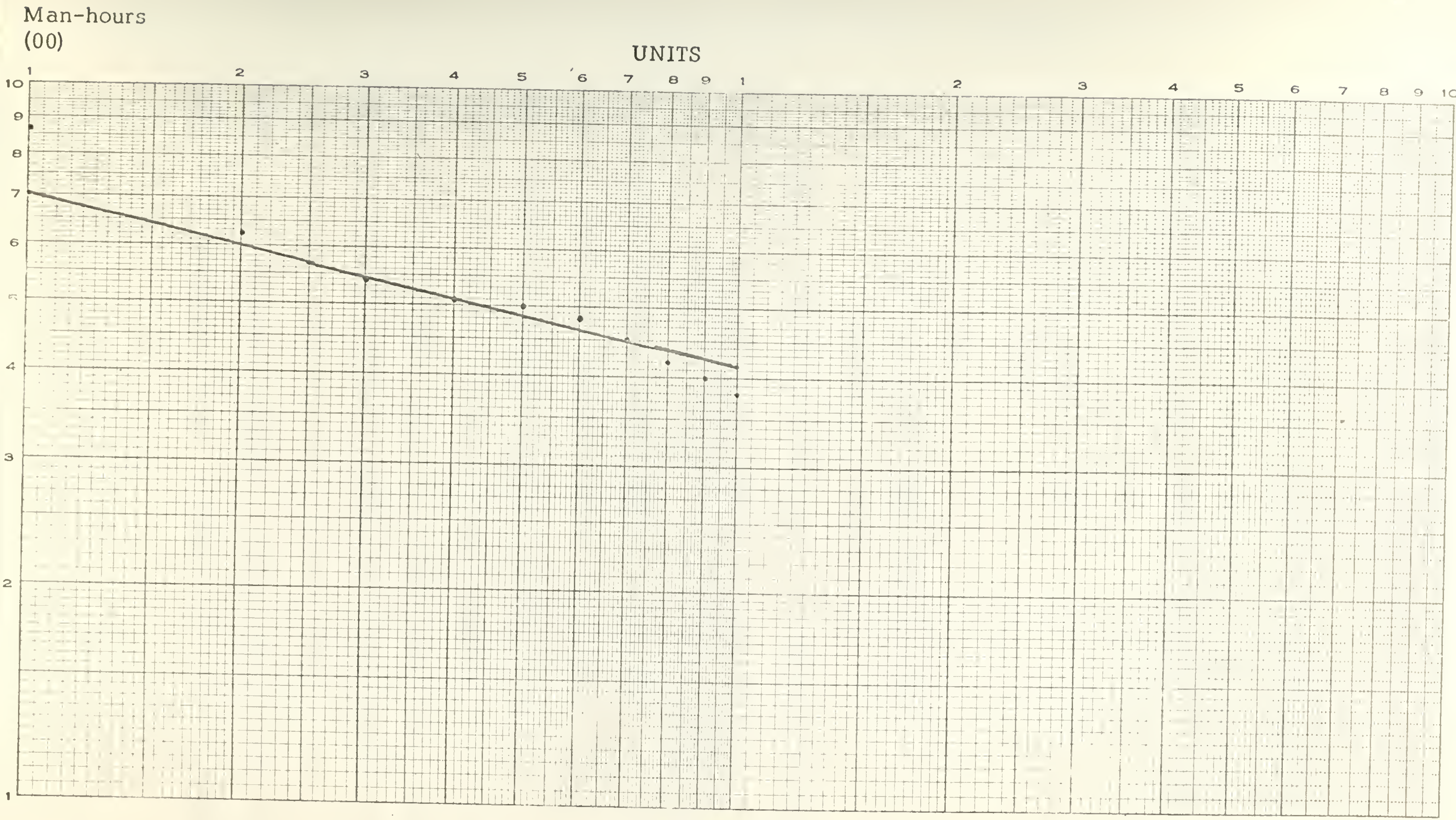

Figure 4
Fitted Learning Curve
By Least-squares Method

in terms of the percentage ratio of unit 1 cumulative average man-hours to unit 2 cumulative average man-hours. In other words, the answer for y will yield the slope or the per cent learning curve.

$$\text{Log } y = \log 100 + (-.2152) \log 2$$

$$= 2 + (-.2152)\ .3010$$

$$= 2 - .0648$$

$$= 1.9352$$

$$y = \text{antilog } 1.9352 = 86\% \text{ learning curve.}$$

E. APPROACH OF THIS STUDY

When new aircraft are to be inducted into the Navy's overhaul or rework program, BuWeps promulgates the requirements or specifications that constitute an overhaul. These specifications stipulate the various tasks that are to be performed on each and every aircraft, of the specified model and configuration, that is subject to overhaul. In order to determine schedules, manning levels, etc., an estimate of the number of direct labor hours necessary to accomplish an overhaul must be made. Based on the job content of the specifications, this estimate is arrived at through the use of Engineered Performance Standards (EPS) and similar scientific time and motion methods. This estimate or standard is called a Weight Factor and is expressed in thousands of hours. A Weight Factor of 8.3 assigned to

an overhaul would indicate that the estimated number of direct labor hours to complete the overhaul is 8,300.

Assuming that the Weight Factor was reasonably estimated and that the job content of the overhaul remains unchanged, the Weight Factor stands for the life of the overhaul. If the learning curve phenomena is at work in the Navy's overhaul program, then the many management decisions that are based on Weight Factors are incorrect to the extent of the existence of this influence. It is the search for the answer to this question of applicability of the learning curve theory that this study is primarily directed.

One of the most important considerations in a study of this nature, is to insure that the data to be analyzed are comparable. If the individual aircraft of a given model and configuration that undergo overhaul are identical in all respects and are subject to the same work during overhaul, then the question of comparability of unit direct labor hours is solved. In the Navy's overhaul program this is not the case. Individual aircraft differ as to installed equipments, and field changes. Additionally, as an established overhaul of a given model and configuration progresses, decisions are made to change the specifications and consequently the job content of an overhaul. These decisions result in the assignment of a different Weight Factor for the remainder of the overhaul run.

In the conduct of this study, these complications were recognized and the source data were adjusted in order to achieve comparability, the method used to refine the data is explained in Chapter III.

The data used in this study were gathered from the Bureau of Naval Weapons, Washington, D. C., and the Overhaul and Repair Department of the U. S. Naval Air Station, Alameda, California. Data were collected for only three aircraft types due to the magnitude of the manipulations necessary to refine and interpret the data. However, the object of the study is to determine the applicability of the learning curve to the Navy's aircraft overhaul program, not to determine learning curves for all types of aircraft overhauled. For this purpose, the data used seem adequate.

F. BENEFITS TO BE DERIVED FROM THE STUDY

In the area of the Navy's overhaul program, it is hoped that this study is but the beginning of a number of studies to validate and refine the applicability of the learning curve. Assuming that this study is successful in proving the relationship of the learning curve theory, there are certain measures that must be taken before the benefits to be derived from the application of the theory can be achieved.

First, it would be necessary to modify the cost accumulation

system in order to obtain meaningful and comparable cost classifications. The current system, that fortunately collects costs by individual aircraft, lumps dissimilar costs into the same account. The extraction of these dissimilar costs into their appropriate components in this study has been ponderous and at times, the method necessarily arbitrary.

Having accomplished this phase, it would next be necessary to conduct detailed studies to ascertain the learning curves that pertain to the various types of aircrafts, i.e., fighters, bombers, transports, helicopters, etc. These curves would then serve as one of the bases for management decisions in the overhaul program.

Additional studies should be directed at the development of an overall learning curve for aircraft overhauls. Different sizes and composition of basically similar items can be compared for learning curve purposes by using the relative weights of the units as a basis of comparison. In the airframe industry, the universally accepted measurement is man-hours per pound of airframe weight.

The results of this work would not only be beneficial at the Bureau of Naval Weapons level but would also serve the interests of the local overhaul activities. At the Bureau level, more valid and meaningful input data would be available for the formulation of optimal overhaul schedules. These refined schedules then permit effect-

ive and efficient resource allocations. At the activity level, the curves would be used to form sound management decisions on (1) equipment requirements, (2) manning levels, (3) inventory levels, (4) budgeting, (5) and induction of work units.

Another interesting benefit that it is believed will be achieved, is psychological. The practice in many airframe plants is to allocate to the foremen of the various shops a given number of man-hours for each lot of airframes. These hours are usually obtained by a linear extrapolation of the learning curve. With the knowledge, on the part of the foremen and workers, of what is expected, it is not unusual that the actual man-hour cost per lot follows the curve from which the allotment of hours was estimated.[14] This brings to mind the definition of a "happy" sailor; a sailor who knows what is expected of him. From a psychological standpoint people are more likely to respond when they know what they are supposed to do and particularly when this offers a challenge. Both of these points are extant in the application of the learning curve.

As Overhaul & Repair Departments are converted to commercial-type accounting under Naval Industrial Fund (NIF) procedures, learning curves will be particularly valuable in estimating costs for sought

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[14] Asher, op. cit., pp. 102-103.

after overhaul contracts. Actually, learning curves have more immediate relevance in a profit and loss type operation similar to that envisioned in NIF operations; in order to be competitive, an activity must be able to realistically forecast its costs.

Finally, it is hoped, that the success acquired in the aircraft overhaul program through the use of learning curves, will inspire other Bureaus of the Navy Department, that conduct construction or overhaul programs, to investigate the susceptibility of their programs to the use of learning curves.

G. CAUTIONS AS TO THE USE OF FINDINGS

The findings of this study can not be construed as an absolute identification of learning curves. The findings do indicate the existence of the learning curve theory in the Navy's aircraft overhaul program. This study was designed as an exploratory probe into the area in the interest of stimulating a response on the part of management. It is hoped that this response takes the form of studies that will in fact be able to statistically identify the various curves that the findings of this study indicate exist. There is a wealth of data available in the filing cabinets of all Overhaul & Repair Departments. A feeling of sincere satisfaction and accomplishment will be had by the managers who analyze these data, identify the learning curves at work in their departments, and use this unique tool in decision making

processes.

There are certain cautions that must be heeded in using the data accumulated by cost accounting systems. Axiomatic with the learning curve theory is the fact that total unit costs should also evidence a negative slope. A curve may portray improvement but a look at labor or material <u>dollar</u> costs may show an increase. If labor dollar costs are up, an investigation may disclose that more skilled and consequently more expensive workers are being hired. This increased skill will undoubtedly reduce direct labor hours, but at the expense of increased direct labor <u>dollar</u> costs. Concerning increased material costs, if workers are not refurbishing ancillary components but rather drawing new units from stock, direct labor hours can be expected to be reduced but at the expense of increased material costs. Trade offs of this nature must be viewed in the light of their combined contribution to efficient operations.

Realizing the manipulation that cost data get before they are presented to management in a finished report, it is only natural to spot check the validity of data to be used. At different periods in the learning curve, time studies should be conducted of actual overhaul performance and the results verified with the data generated by the accounting system.

What is said about the difficulty of comparing apples and or-

anges pertains to the comparison of units in the learning curve theory. If the job content of each unit is not the same then a true basis for comparison does not exist. As with all things in this universe, 100% reliability is almost impossible to achieve. Therefore, a certain tolerance of differing job content is acceptable. This tolerance will be greater in an overhaul program than a manufacturing one due to the nature of the work however, tolerances that materially affect the rate of change of the curve must be investigated and necessary adjustments effected.

CHAPTER II

REVIEW OF SELECTED STUDIES

A. NAVY STUDIES

Of the various studies conducted in the area of learning curves, the one most pertinent to this study is a study conducted in 1957-58 by Kenneth W. Webb.[1] At the time he was a researcher working for the Bureau of Naval Weapons. The purpose of his study was to explore the existence of learning curves in airframe and engine overhauls.

Webb's conclusions are ambiguous and it is believed have clouded the issue of learning curves at work in Navy overhaul programs. In his conclusions he states that the overhaul process has a phenomenon at work that obscures the learning curve. This obscuring process he, "...found to be the opposite to learning curves and because of this it was called 'anti-learning curves'." The justification of the reason for the existence of an anti-learning curve is not

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[1]Kenneth W. Webb, "Learning Curves in the Rework of Airplanes and Engines" (Washington: Bureau of Naval Weapons, 1958). (Mimeographed.)

explained other than by the statement that it is, "... possibly due to technological complications and increasing age of the aircraft."[2] This is slim justification for such a novel and shattering hypothesis.

Other than identifying the existence of the so-called anti-learning curve from empirical data, Webb does not develop the reasoning for his hypothesis nor does he evolve a method for predicting the applicability of an anti-learning curve to future overhauls.

For one to doubt the existence of an anti-learning curve is to infer that Webb's basic data is suspect, that his data lack comparability. It is believed that Webb's data was not homogeneous and therefore his anti-learning curve theory lacks support.

The data used by Webb in his study was extracted from the Section C's of the quarterly report "Industrial Cost and Performance Report" (hereinafter referred to as, "Cost Report") submitted to BuWeps by each Naval and Marine Corps Air Station having an Overhaul and Repair Department. The data contained in these reports are not a valid source for learning curve studies because (1) the data lacks chronology, and (2) the job content of completed units varies.

It is most important in learning curve studies that the data be analyzed in a chronological sequence. Without this, one of the fundamental concepts of the learning curve theory is nullified, namely, that

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[2] Ibid., p. 2.

the constant reduction applies to the <u>succeeding</u> doubled quantity. The Cost Reports are prepared and submitted in accordance with requirements of a Bureau of Naval Weapons handbook.[3] As directed by the handbook, Section C consists of, "Standard direct hours per unit and total man-hours and charges <u>reported on a closed job order basis</u> by unit completions by model and configuration on aircraft and engine programs." (Underscoring supplied.)

It is this reporting on a closed job order basis that destroys the chronology of the reported units. Physically completed units are not reflected on this report until all accounting charges have been lodged and the account or job order officially closed. Normally it would be considered that the accounting lag would apply to all units equally and thus the completed units would be reported in sequence. This however is not the case. Many units, in addition to overhaul, will require concurrent repair. The execution of the repair requires the purchase of certain materials and it is the delay incident to the charging of job orders for these purchases that disrupts the sequence of reporting.

There is another procedure that is common in Overhaul and

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[3] Aeronautics Overhaul and Repair Cost Accounting Handbook (Washington: Bureau of Naval Weapons, CH-3, 1960), Part B, Sec. 4201, p. 4-5.

Repair Departments that causes a disruption in the sequence of reported completions. This procedure is known as "back-robbing". Simply explained, "back-robbing" means that when outstanding purchased material will delay the completion of a unit, similar material is "robbed" from a unit further down the schedule and the original unit thus completed. This "back-robbing" is kept up until the purchased material is received at which time it is used to complete the last unit "robbed". The problem that this creates in connection with the Cost Report is that the original unit may have been physically completed in month one but the outstanding purchase may not have been charged to the unit's job order until some four or five months later. As far as the Cost Report is concerned that unit would not show up as completed until the fourth or fifth month.

Another factor that is very important in learning curve studies is the comparability of the source data. There are two causes that affect the comparability of the data reported in Cost Reports (1) a modification of the overhaul specifications and (2) the service changes to be incorporated in an aircraft during overhaul.

The first of these is recognized in the report since completed units of a given model are reported on the basis of a weight factor. The weight factor determines the number of direct labor hours allowed for a given set of overhaul specifications. Consequently, a modifi-

cation of specifications for the overhaul of a given aircraft model would show up as a separate entry because it would have a different weight factor.

The problem of the service changes is not recognized by the Cost Report. Due to the rapid technology that is characteristic of aircraft, the Navy from time to time promulgates aircraft service changes that can be accomplished at the squadron level in order to improve the safety or performance of an aircraft model. Depending on the press of operational commitments, these changes may or may not be made prior to an aircraft's overhaul. For this reason, the individual aircraft of a particular model vary as to installed equipments and other modifications. One of the objectives of an overhaul is to correct this individuality by incorporating in deficient aircraft the necessary aircraft service changes. As a result of this feature of overhauls, the job content of an overhaul will vary from plane to plane. Of 120 A4D-2's overhauled at NAS Alameda less than 15% were comparable as to service change labor hours. As a percentage of the total overhaul hours, the direct labor hours attributed to service changes ranged from a low of 3% to a high of 41% with an average of 20%.

From the foregoing it is easy to see the distortions that are created by the lack of chronology and comparability of source data.

It is reasonable to assume therefore that Webb's anti-learning curve is the product of heterogeneous source data and not the product of an extant force that must be considered in applying learning curves to Navy overhaul programs.

B. RAND CORP. STUDIES

The RAND Corp., an independent non-profit organization devoted to scientific research in the interest of the national security and welfare of the U. S., has conducted a number of studies of learning curves in the airframe industry. These studies are valuable from the standpoint of the coverage they afford the learning curve theory.[4] Unfortunately none of these studies treat the application of the theory to rework programs but rather its application and use in the manufacturing of airframes. Many of the findings however do have applicability to rework programs and as such these studies are a source of refinements and sophistications that future researchers should not overlook.

C. STANFORD RESEARCH INSTITUTE STUDY

One of the well known studies of the learning curve in the airframe industry is the study conducted by the Stanford Research Institute under contract with the U. S. Air Force.[5] One of the conclusions

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4See Bibliography under RAND Corp. for listing of these studies.

5<u>Relationships for Determining the Optimum Expansibility of the Elements of a Peacetime Aircraft Procurement Program</u>, Stanford Research Institute, prepared for Air Material Command, USAF, 1949.

of the report is the introduction of the "B" factor. The study contains the belief that the function,

$$y = \frac{a}{\sqrt{x + B}}$$

is a better expression of the relationship between man-hour cost and cumulative output, than the conventional equation developed by T. P. Wright.

The B in this formula is now commonly referred to as the "B" factor. One of the basic assumptions in this formula is that the rate of change or improvement is constant for a company with no previous experience in airframe manufacturing and further this rate of improvement is 29.3% or a learning curve of 70.7%. Therefore, in order to compensate for companies that have previous familiarity a "B" factor is assigned. If B equals O for a new company to the industry, then the above equation can be written,

$$y = ax^{-.5}$$

which is the same as Wright's equation except that his b is replaced by the value -.5.

The Stanford formula was the result of an investigation of twenty-nine World War II models and has not been critically tested on postwar data. Harold Asher in his study argues that the 70.7% curve is not appropriate for postwar models and therefore the use of the

Stanford formula would require the introduction of an additional parameter n and the formula would then take the form,

$$y = a(x + B)^{n}.$$ [6]

There is no question concerning the dependent relationship between the "B" factor and the exponent n. However Asher questions the wisdom of trying to quantify two parameters when one would suffice. His reasoning appears sound since today the conventional form expressed by Wright is the one most widely used.

Using the Stanford formula the learning curve on log-log paper shows a concavity at the beginning of the curve when the "B" factor is greater than O. The rationale is that an experienced company will encounter various rates of improvement during the early stages of a production run. One writer identified such concavity as the result of hiring inexperienced crews at different points in time during the first group of airframes.[7]

It is reasonable to accept Asher's argument and consequently the Stanford formula will not be used in the analysis of Navy overhaul data in this study.

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[6]Asher, op. cit., pp. 108-109.

[7]G. W. Carr, "Peacetime Cost Estimating Requires New Learning Curves," Aviation Vol. 45 (April, 1946), pp. 76-77.

CHAPTER III

DATA AND METHODS USED

A. BUWEPS PERFORMANCE SUMMARY REPORTS

Initially it was intended to analyze data for 10 different plane types at two different overhaul and repair activities within each of the rework programs. These rework programs are classified as: overhaul, overhaul/conversion, progressive aircraft rework (PAR), PAR/conversion, and modified PAR. Each quarter BuWeps prepares a "Performance Summary Report for Overhaul and Repair Departments". In addition to other information this report contains a summary of completed aircraft by rework category. Within each category, this summary is broken by plane type and then activity. Opposite each activity are entries of the number of particular aircraft produced, the BuWeps weight factor assigned, the job order completions, and the average man-hours spent per aircraft.

Believing that these reports might serve as a source of information for the study, BuWeps was requested and kindly furnished reports for the latest eight quarters. In order to properly test the learning curve theory, it was necessary to select only those aircraft for which

data were available from unit number one on. On this basis most of the plane types contained in the reports could not be used since data on the initial units overhauled were not available. Consequently three plane types were selected: the P2V-7S that commenced PAR in January 1961, the A4D-2 that commenced PAR in January 1960, and the A4D-2N that commenced PAR in January 1961. Each plane type was undergoing PAR at two activities; all three were being handled by NAS Alameda, the A4D-2 and the 2N were in the lines at NAS Quonset Point and the P2V-7S was also being handled by NAS Norfolk.

The initial plots by plane type and activity of the data from the Performance Summary Reports was discouraging. There were very few distinguishable trends and where they did show up, in most cases they were positively sloped instead of negatively. At this point it looked like K. W. Webb's "anti-learning curve" was a factual phenomenon. Without a justification for the existence of the phenomenon it was believed that the best course of action was to check the validity of the source data.

A trip to the Overhaul and Repair Department of the NAS Alameda verified the suspicion that the data was invalid for learning curve purposes. It was brought out that the average man-hours reported in the reports was on the basis of completed job orders and they they contained man-hours required to incorporate deficient aircraft service

changes. From the standpoint of the learning curve this contaminated the data in terms of chronology and comparability.[1]

In view of this unforeseen problem it was decided that the coverage of the study would have to be reduced. In lieu of the ten different plane types at two different activities for each of the rework programs, it was decided to restrict the study to the three plane types mentioned earlier and only for the data available at NAS Alameda.

B. DATA ACCUMULATED FROM NAS ALAMEDA

Management control of the Navy's aircraft overhaul programs is in part exercised through the analysis of two basic reports, the Industrial Cost and Performance Report (identified earlier) and the Industrial Production and Performance Report (hereafter referred to as, "Production Report"). Reports are submitted to BuWeps by each Naval and Marine Corps Air Station having an Overhaul and Repair Department. Certain sections of these reports are submitted each month and other sections are submitted on a quarterly basis.

The sections that are of interest here are the sections that report completions by individual aircraft type. The Cost Report had to be discarded as a source of data because, as previously indicated, completions are reported on the basis of closed job orders and not

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[1]See Chap. II, Section A, for an explanation of the problems of chronology and comparability.

physical completions. The Production Report was accepted as a starting point since it reported individual units at the time of physical completion. Additionally, it reported the start and complete date for each unit and thus it was possible to make adjustments for individual planes whose completion date was delayed due to lack of material, etc.

Two problems associated with these data were (1) within each plane type different weight factors were assigned as a result of changes in the overhaul specifications, and (2) the data contained no indication of the man-hours attributed to aircraft service change work. For the purpose of determining the applicability of the learning curve, the data required smoothing so that aircraft to be compared were in fact comparable as to job content.

C. METHOD OF SMOOTHING DATA

The smoothing operation for each plane type was conducted in two parts (1) the extraction of the man-hours required to accomplish the aircraft service change work, and (2) the reduction of the data to a common weight factor. Due to the method of cost accumulation in use, it was not possible to obtain exact data to accomplish the smoothing.

Usually the change in specifications of the overhaul added or eliminated elements of the overhaul. In no case did a change modify

all elements of an overhaul. Consequently the learning by workers was carried over from one change to the next as long as a change did not increase the weight factor appreciably. For instance, if a plane had a weight factor of 2.2 and a change increased this to 6.1, then there would be very little learning carried over to the new change.

The first problem to be resolved was to determine the service change man-hours applicable to each individual plane. Separate job orders had not been set up to isolate this information. The next best thing was to secure for each plane the service changes that were accomplished and then to sum the Engineered Performance Standard (EPS) man-hours assigned to each change. By subtracting this value from the total man-hours charged to the plane it was felt that a comparable base could be achieved for all planes of a given weight factor. It was recognized that the EPS man-hours were only estimates but it was believed that the error in these estimates was not significantly different than the error contained in the weight factor estimates.

Having extracted these man-hours it was still necessary to solve the problem of different weight factors for a given plane. This problem only pertained to the A4D-2 and the 2N as the P2V-7S only had one weight factor assigned. In the A4D-2 the problem was a decrease in weight factors and in the A4D-2N an increase. If the

estimating error between the weight factor and the actual man-hours prior to a change, was the same as after the change, then this relationship could serve as a basis for normalizing the data. In the case of the A4D-2 the error before change was 41% and after change was 39.4%. For the A4D-2N the error before change was 25.2% and after change was 26.6%. Since these differences are insignificant they were disregarded.

An example may clarify how this procedure works. Assume a weight factor of 8.0 is assigned to an overhaul. On the average, the actual man-hours used is 6000. The estimating error here is 25%. Next the specifications of the overhaul are changed and the new weight factor assigned is 6.0. If the estimating error for this weight factor is the same as the 8.0, then the actual man-hours used will be 4500. To normalize these data on the basis of the 6.0 weight factor it is necessary to reduce the 6000 man-hours associated with the 8.0 weight factor by 25%. Doing this, the normalized man-hours are reduced from 6000 to 4500. In this case it would indicate that there was no learning since it took an equal number of man-hours, 4500, to do the same work at two different time periods.

The initial weight factor assigned to the A4D-2N was 1.8 representing 1800 man-hours estimated by BuWeps to complete the overhaul. A subsequent change in the specifications of the overhaul

changed this weight factor to 2.5. In order to normalize the data on the basis of 1.8, the actual man-hours of the units assigned a weight factor of 2.5 were reduced by 26%. A 40% adjustment was used to normalize the data of the A4D-2.

At this point the raw data had been smoothed and were ready for plotting. The plotting disclosed additional problems that are covered in the following sections.

D. PLOTTING OF DATA

An initial analysis of the smoothed data revealed considerable fluctuation among the first units of the P2V-7S. Further, this beginning variation had a significant distorting effect on the cumulative average man-hour calculations. The magnitude of this fluctuation can be more fully appreciated if the data are plotted in arithmatic graph paper. Figure 5 shows the plotting of the individual units. As can be seen there is considerable fluctuation in the data but particularly among the first twelve units. Superimposed on this plotting is a regression line to indicate the trend of the data. This line was fitted by the method of least-squares. As indicated by the line, there is a declining trend in the man-hours however, the amount of decline is not too significant in view of the number of units involved and the scale used on the Y axis. Over the twenty-eight units plotted, the reduction in man-hours was from 5725 to 5550 or a 3%

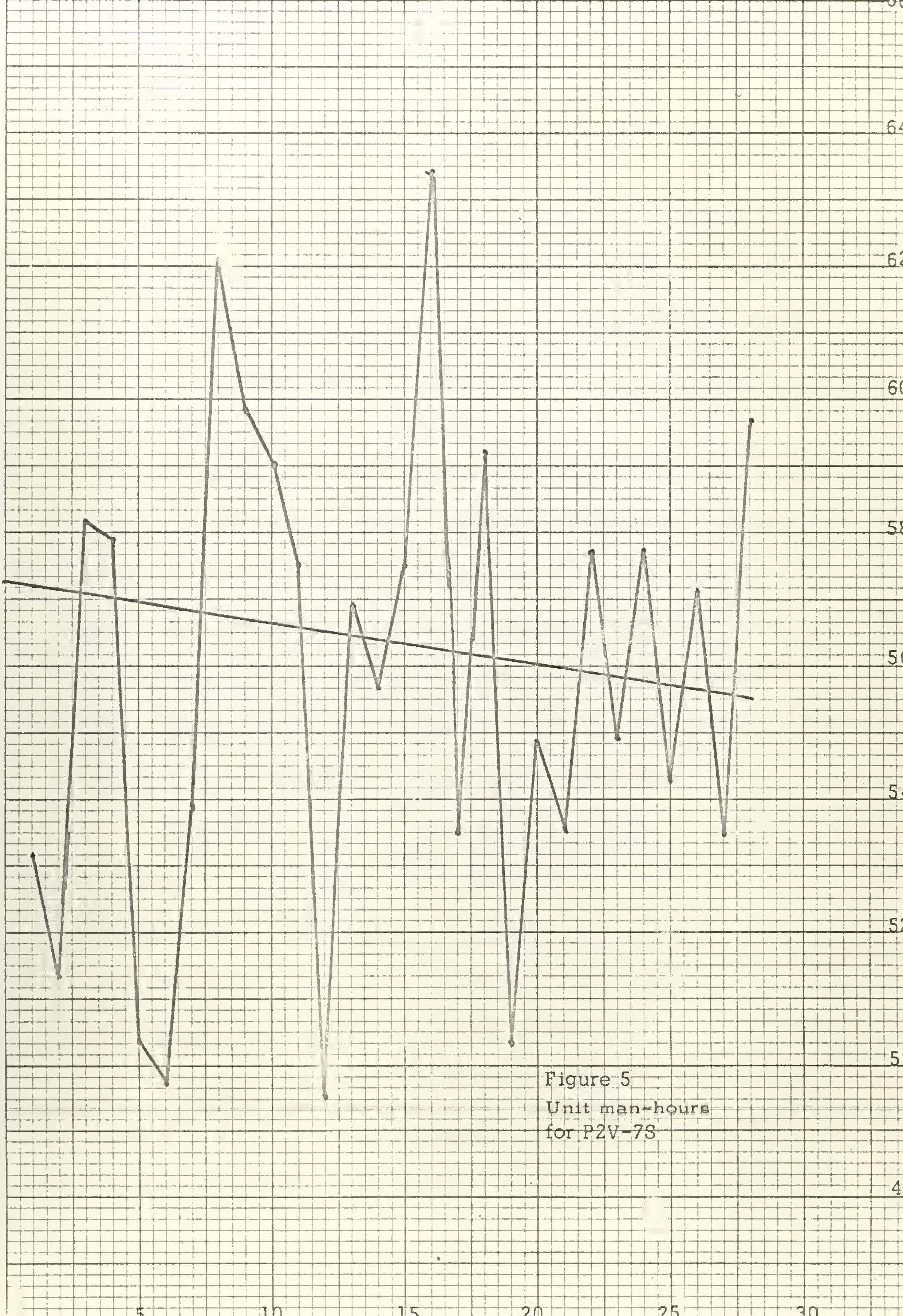

Figure 5
Unit man-hours
for P2V-7S

reduction. In their relationship to this line, the first units appear to be decidedly understated.

The distortion that the fluctuations of the initial units had on the cumulative average man-hours is shown in Figure 6. At about unit 10 this distortion is overcome and the plotting takes on a more normal pattern indicating a reduction in man-hours. The reason for the fluctuation in the first units of the P2V-7S could not be determined but there are a number of possible explanations. The one that is accepted as the most likely is faulty cost recording at the outset of the overhaul run. It is not unusual for workers who are assigned to new work to initially record charges against former work because the job order numbers of the former work are fresh in their memory. After a short period of time on the new work, these old numbers are forgotten and this source of erroneous cost recording eliminated.

The data plotted for the three plane types were from the beginning of the particular overhaul through physical completions in December 1961. The overhaul of the A4D-2 commenced in January 1960 and the overhauls of the A4D-2N and the P2V-7S in January 1961. The overhaul completions of the A4D-2 prior to 1 July 1960 presented a little problem since prior to 1 July 1960 overhaul costs were accumulated on a lot versus an individual unit basis. The size of the lots varied from two to six aircraft. In order to make an adequate

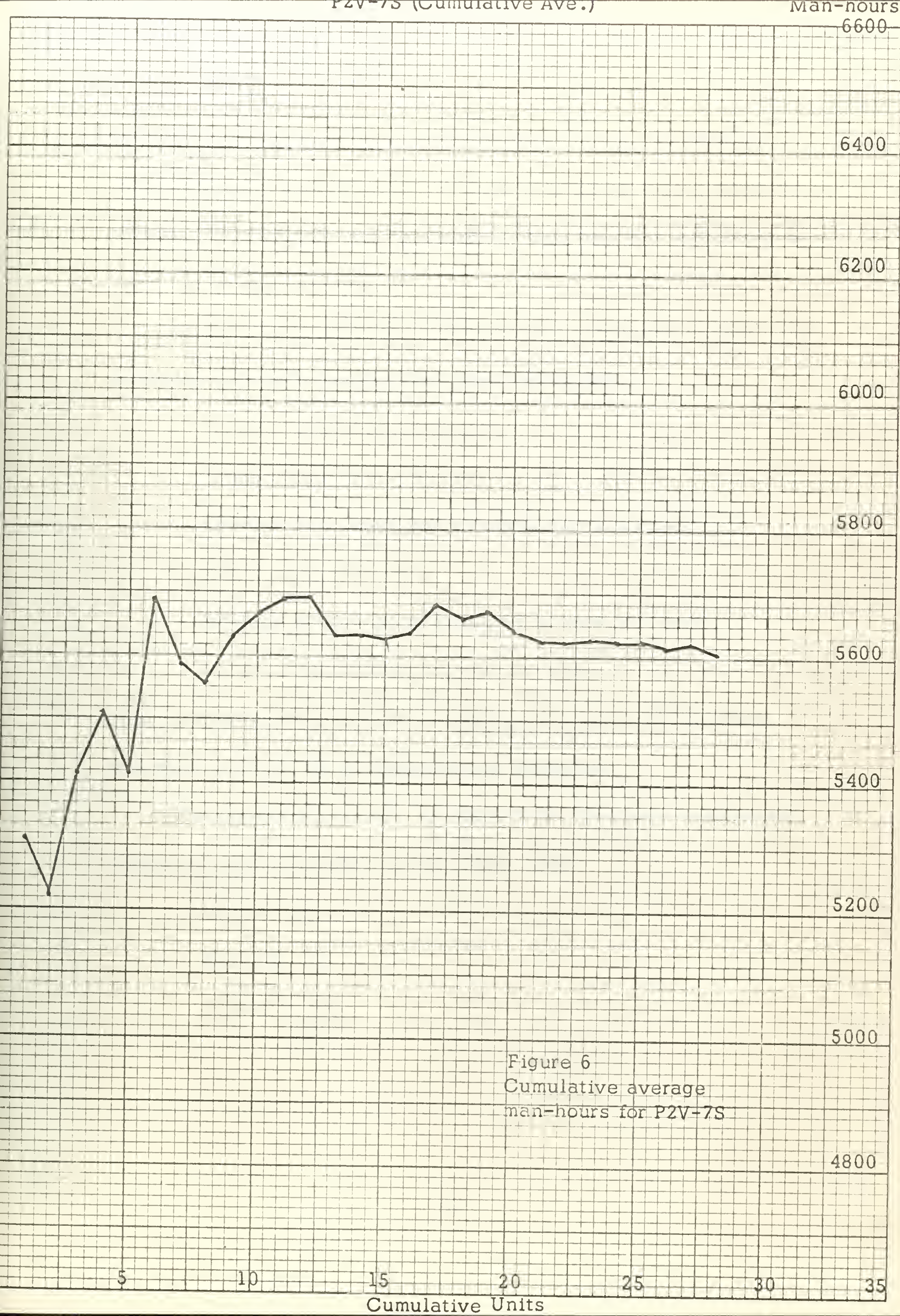

Figure 6
Cumulative average
man-hours for P2V-7S

analysis of the applicability of the learning curve, the data for these first units would have to be included. The question was how to arrive at meaningful and comparative data that was indicative of the actual costs incurred.

By extracting information from various completed records, the following data was compiled for almost every lot:

Number of aircraft in the lot,

Average man-hours per lot,

Average man-hours per lot attributed to aircraft service change work,

BuWeps weight factor assigned to each lot, and

Physical completion date for each lot.

This information was sufficient to arrive at a smoothed average man-hour cost per lot in chronological sequence.

The number of aircraft, by plane type, that were overhauled during the period covered by this study was:

A4D-2	201
A4D-2N	51
P2V-7S	28
	280

CHAPTER IV

RESULTS OF RESEARCH

A. PRESENTATION OF DATA

As stated earlier, the raw data by individual units, and by lots in the beginning of the A4D-2 overhaul, were smoothed by eliminating aircraft service change work, and by adjusting for variances in weight factors. The purpose of this smoothing was to achieve comparability of data. Appendix A is a tabular presentation of the data for the A4D-2N. Shown are the raw data, the adjustments for service changes and weight factors, the adjusted man-hours, and the cumulative average man-hours.

The data for the A4D-2N was normalized on the basis of a weight factor of 1.8.[1] Thus the column titled, "Weight Factor Adjustment" reflects values only when the weight factor of a unit is other than 1.8. Appendix A is representative of what was done for each plane type consequently detailed tables are not included for the

[1]The method of normalizing weight factors is explained in Chapter III, Section C.

A4D-2 and the P2V-7S. There were no weight factor adjustments necessary for the P2V-7S since only one weight factor, 8.3, was assigned.

For plotting purposes, the "Cumulative Average Man-hours" column of Appendix A was used for the A4D-2N. Tables 3 and 4 contain the data that were used for the A4D-2 and the P2V-7S. It is to be noted in Table 3 that there are no data for the plotting of man-hours for units 1-29. The reason for this is that there were certain questions concerning the applicability of cost data to specific units for the first thirty aircraft in the overhaul. Rather than arbitrarily assigning costs to specific units and possibly distorting the data, it was decided to lump all pertinent costs together for the first thirty aircraft and calculate an average man-hour cost for these units. Additionally, due to the large number of units involved in this plane type, and the difficulty in plotting the individual units after thirty, plotting was restricted to ten unit increments.

B. DETERMINING LINES OF REGRESSION

The exciting part of any study is that portion that evaluates the hypothesis of the study. All the work that precedes this portion is like a prologue. After plotting the smoothed data for each plane type on log-log paper, a discernible negative slope was evident in two out of the three graphs. Rather than constructing the lines of regression

TABLE III

SMOOTHED DATA USED FOR PLOTTING LEARNING CURVE OF A4D-2

UNIT	CUMULATIVE AVE. MAN-HOURS	UNIT	CUMULATIVE AVE. MAN-HOURS
30	1755	120	1597
40	1720	130	1576
50	1653	140	1556
60	1672	150	1556
70	1620	160	1553
80	1594	170	1541
90	1591	180	1534
100	1596	190	1528
110	1599	200	1524

TABLE IV

SMOOTHED DATA USED FOR PLOTTING LEARNING CURVE OF P2V-7S

UNIT	CUMULATIVE AVE. MAN-HOURS	UNIT	CUMULATIVE AVE.MAN-HOURS
1	5310	15	5635
2	5219	16	5642
3	5417	17	5683
4	5510	18	5664
5	5414	19	5677
6	5689	20	5644
7	5586	21	5636
8	5561	22	5623
9	5633	23	5629
10	5668	24	5623
11	5690	25	5629
12	5695	26	5621
13	5637	27	5624
14	5640	28	5613

by visual inspection based on the scatter arrangement of the individual points, the lines of regression were determined by the method of least-squares.

The results of the plottings and the lines of regression, by plane type, are reproduced in Figures 7, 8, and 9. Figure 7 shows no points for units 1-29. This, as stated earlier, is due to the questionable nature of the costs identified to specific units for the first thirty aircraft. The regression line however, gives theoretical values for these units based on the actual cumulative average man-hours for units 30 through 200. These values indicate that the first unit should have taken approximately 2630 man-hours and the second unit approximately 2420 man-hours. Dividing 2630 into 2420 yields a learning curve of 90% for the A4D-2.

The regression line for the A4D-2N as shown in Figure 8, identifies the first unit as costing approximately 1800 man-hours and the second unit approximately 1660 man-hours. Dividing the former into the latter yields a learning curve for the A4D-2N of 92%.

Using <u>all</u> points plotted for the P2V-7S, Figure 9, the regression line would be positively sloped and by the method of least-squares would have a value of 101.4%. This would mean that as quantitites overhauled are doubled the man-hours required to accomplish the overhaul would increase by 1.4%. All other things being

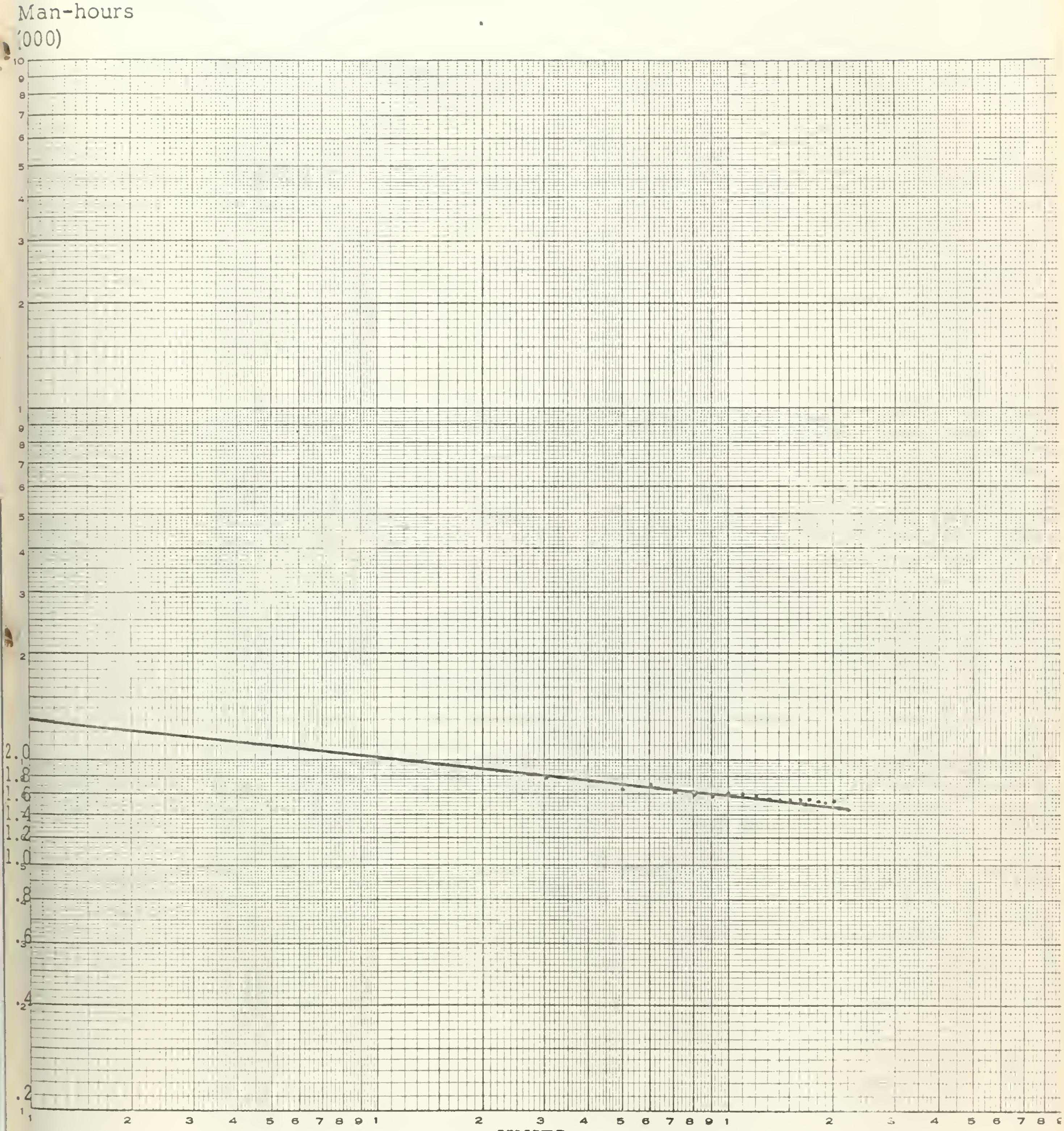

Figure 7
CUMULATIVE AVE. MAN-HOUR LEARNING CURVE FOR A4D-2 (90%)

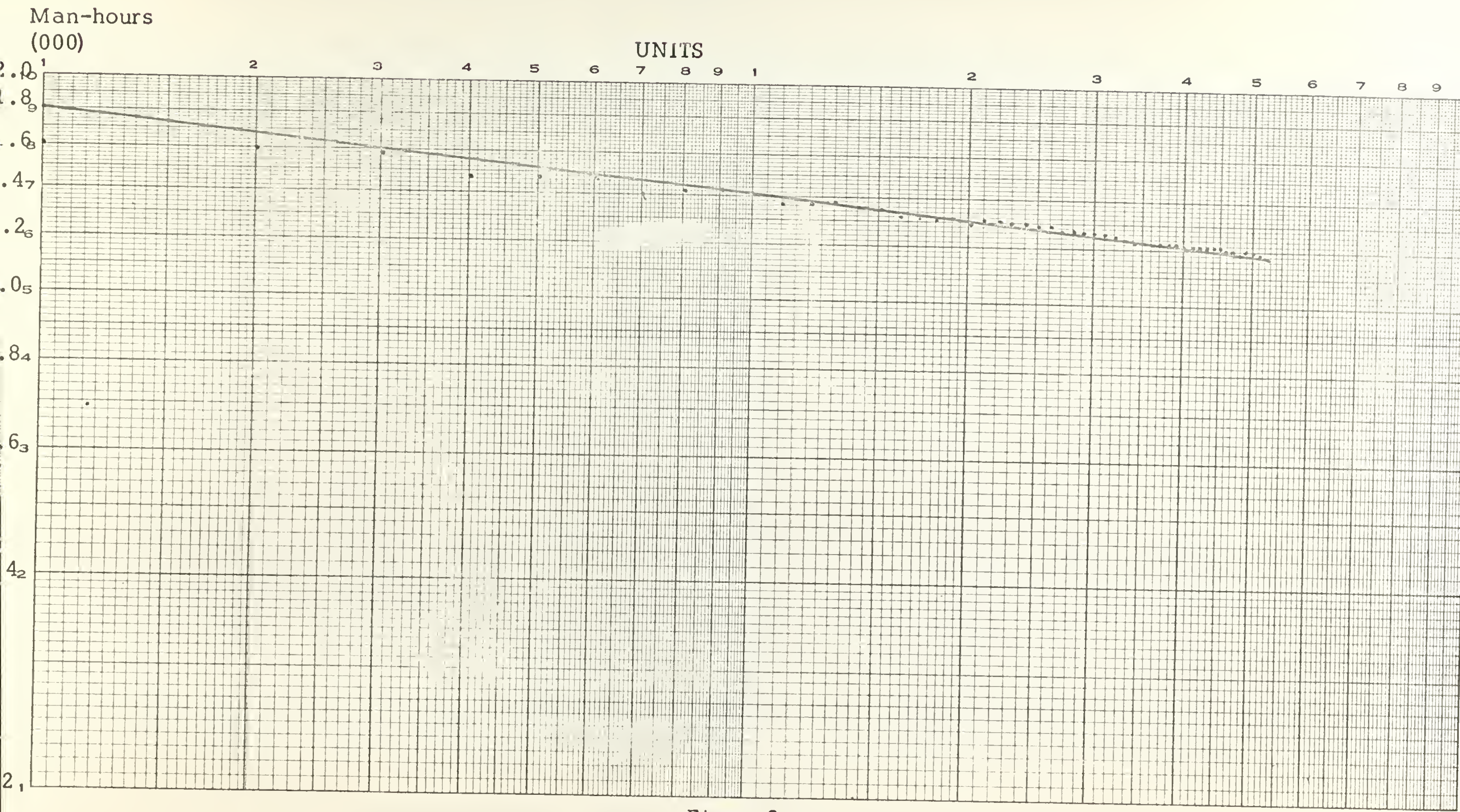

Figure 8

CUMULATIVE AVE. MAN-HOUR LEARNING CURVE FOR A4D-2N (92%)

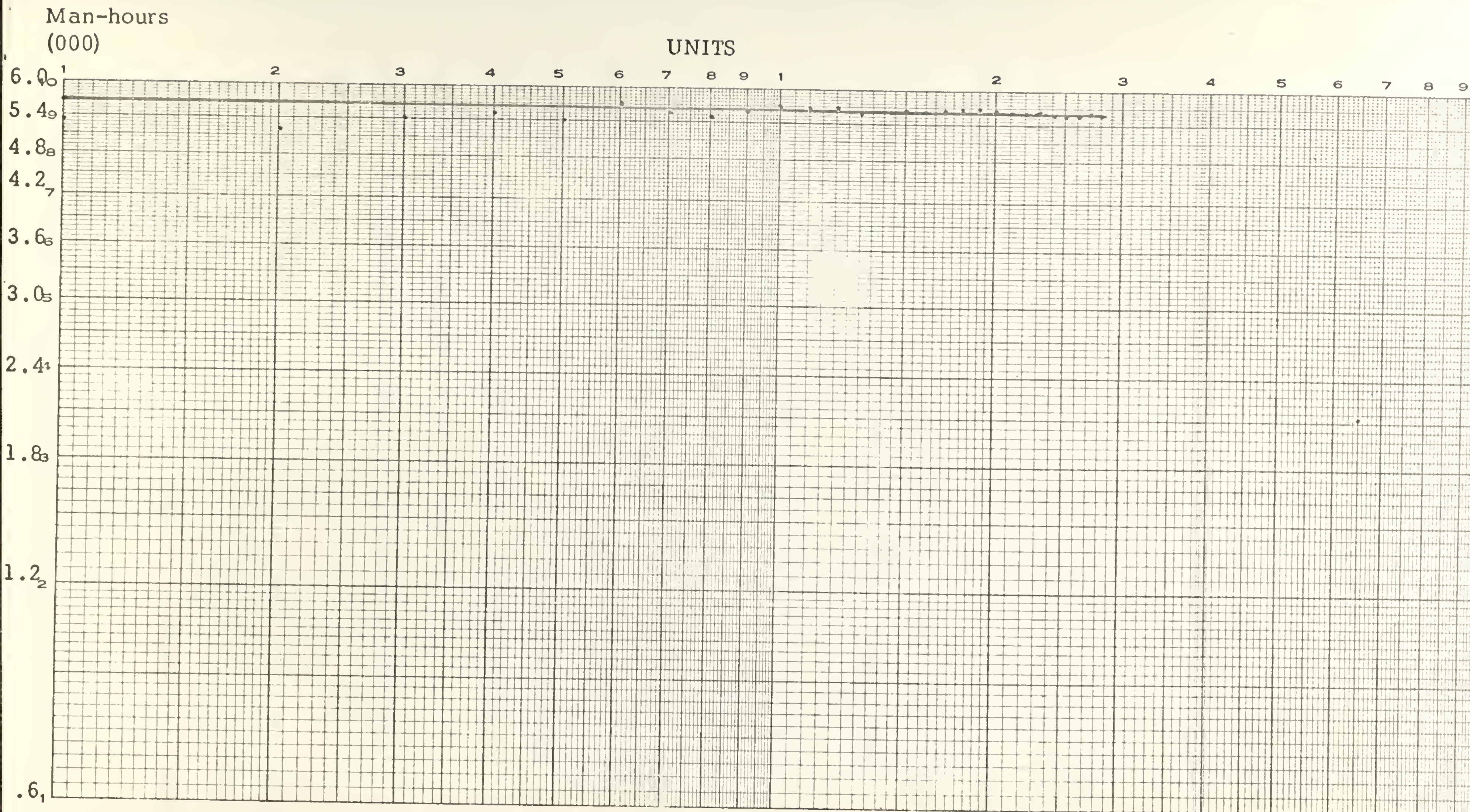

Figure 9

CUMULATIVE AVE. MAN-HOUR LEARNING CURVE FOR P2V-7S (98.7%)

equal, an increase of this nature would indicate an inefficient management and work force. Before attributing such a charge to an organization the data would have to unequivocally evidence an upward trend. An analysis of Figure 9 reveals that the upward trend is restricted to the first five units. In the preceding chapter the suspect nature of the cost data for these initial units was pointed out. Disregarding the plotted points for the first five units and determining the regression line on the basis of cumulative average man-hours for units 6 through 28, the least-squares method yields a learning curve of 98.7%. The reasonableness of disregarding the individual cumulative average man-hours for units 1 through 5 is believed apparent. This does not mean that the man-hours for the first five units was completely thrown out; the plottings for unit 6 through 28 include the man-hours for the first five units since each of these points represents the average man-hour cost of all overhauls completed through the unit indicated. Due to the minimum amount of negative slope involved in the learning curve for the P2V-7S, 1.3%, it is not possible to visually determine the reduction of man-hours from unit 1 to unit 2. As will be noted in Figure 9, the values for units 1 and 2 appear to be the same. Using the method of lease-squares, unit 1 is calculated as having a value of 5610 man-hours and unit 2 a value of 5540. Therefore, for the purposes of this study, the learning curve attributed

to the P2V-7S was accepted as 98.7%.

C. INTERPRETATION OF THE CUMULATIVE AVERAGE MAN-HOUR LEARNING CURVES

Anyone familiar with industrial effort has observed that progress in the effective results of this effort frequently takes place as time passes and the effort is continued. This progress is founded on a multitude of causes whose individual effects vary from time to time. Over a period of time the composite product of these causes is a predictable rate of improvement-the learning curve. The slope of a given learning curve depends on the degree that each of the multitude of causes is in evidence in a particular industrial effort.

In the preceding section the learning curves identified with the three plane types were as follows:

A4D-2	90%
A4D-2N	92%
P2V-7S	98.7%

The different learning curves applicable means that in each of the plane types the various causes that result in improvement were manifest in differing degrees. This section undertakes the interpretation of these differences. The interpretation of the three learning curves will be done on a comparative basis therefore, the 90% curve of the A4D-2 will be used as a point of reference.

In analyzing a decrease in improvement between products of an industrial facility there are certain major factors that must be investigated. The first is a change in management policies and procedures that would create inefficiencies. This was not believed to be a contributing factor as far as this study is concerned and will be excluded from further consideration. The other two major factors that affect a learning curve are (1) the extent of initial planning and tooling, and (2) previous experience or know-how; these two factors were used in analyzing the decrease in improvement of the A4D-2N and the P2V-7S.

Initial planning and tooling can be either adequate or inadequate. In either case, the extent of the planning and tooling has a decided effect on the slope of the learning curve. Careful planning and efficient tooling tend to reduce the man-hours required to produce the first unit. In other words, management has resolved problem areas and incorporated efficient production techniques prior to the commencement of production. The efficiencies accomplished at this point mean that there will be less for the workmen to "learn" during production. This reduction in the amount to be learned during production is reflected by a shallower learning curve. Conversely, poor preliminary planning leaves a considerable amount to be "learned" during production and results in a steeper learning curve.

Referring back to Figure 8, for the A4D-2N and Figure 9, for the P2V-7S, it will be noted that there is no significant reduction in the beginning units of either plane type consequently no apparent evidence of poor planning. Rather, the beginning unit plots indicate adequate planning.

The factor of previous experience is directly related to the percentage that describes a learning curve, i.e., as the amount of previous experience increases the percentage of the learning curve increases.

There is little doubt about the carry over of experience from the A4D-2 to the A4D-2N. These two aircraft are basically the same with the exception of certain configurations that have modified the 2N into a night attack aircraft. Further, the overhaul of the A4D-2 commenced in January 1960 and that of the A4D-2N in January 1961. An example of the effect of previous experience on a learning curve can be made by using the data of the A4D-2N. As explained earlier, the learning curve of the A4D-2N is 92%. If a new learning curve was developed with unit 10 as the first unit and unit 11 as the second unit, etc., then this new learning curve would have a percentage value of approximately 97%. What happens here is that the new learning curve is not credited with the learning that has taken place during the original

curve consisting of nine units. In this case unit 10, unit 1 in the new curve, is being compared to unit 11, unit 2 in the new curve, as a doubling of quantity. From an actual production standpoint unit 10 should be compared with unit 20 and if so, the percentage of the new curve would also be 92%, the same as the original curve.

In the example just cited both curves came from identical overhauls and this is not the case in the A4D-2 and the A4D-2N. Although similar, there are differences and it is these differences that permit a greater amount of learning than the 97% in the example. It is worthy to note that the first unit of the A4D-2N took 1600 man-hours and the unit of the A4D-2 that was completed at the same time took 1397 man-hours. Theoretically this difference in man-hours can be attributed to the new work involved in the night version of the basic aircraft.

In summary then, the difference between the learning curves of the A4D-2 and the A4D-2N can be attributed to previous experience in a similar aircraft.

The same factor, previous experience, is ascribed to the rather high, 98.7%, learning curve of the P2V-7S. This overhaul commenced in January 1961 however, NAS Alameda had been overhauling the P2V-7 since approximately July 1958. Differences in the two aircraft are generally restricted to a sophistication of the anti-submarine

warfare equipment in the 7S. During the period July 1958 and January 1961, NAS Alameda overhauled approximately 83 of the P2V-7 aircraft. It is this extensive experience that accounts for the rather high 98.7% learning curve.

No effort was made to arrive at an over-all average for the three plane types. Since this was a limited study it was not believed that any real significance could be attached to such an average. The method of arriving at such an average would be the same as used by the airframe industry in their learning curve work. All data would have to be reduced to man-hours per pound of airframe. The definition of an airframe's weight is contained in the "Instructions for the Completion of Aeronautical Manufacturers Planning Reports".[2]

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[2]Approved September 1, 1950 and February 1, 1951, by the U. S. N., Bureau of Aeronautics, and the U. S. A. F., Air Material Command.

CHAPTER V

SUMMARY AND CONCLUSIONS

A. REVIEW OF STUDY

This study was prompted by the outstanding success of learning curves in the airframe industry for the past fifteen years. The value of these curves to the airframe industry is their unique ability to forecast with reasonable accuracy:

1. Production costs for purposes of pricing,
2. Costs of major design changes,
3. Costs on which to base "make or buy" decisions, and
4. Labor and facility requirements for planning purposes.

The anecdote contained in the Preface points out this unique predictive ability of the learning curve.

It is believed that this proven management tool can be successfully applied to Navy production and rework programs. Prior to applying a new technique, it is necessary to understand the process that the technique employs. Chapter I explains the learning curve and its basic theory that costs decline by some constant percentage as the total quantity of units produced is doubled. A knowledge of the theory

implies a knowledge of the relationship of each unit to every other unit, e.g., unit 21 would not be compared to unit 22 to prove the learning curve, but rather unit 21 would be compared with unit 42-- a doubling of quantity.

In using data for the construction of a learning curve, tests of chronology and comparability must be conducted. If data is not plotted in the sequence of occurrence, the ability of the curve to reflect actual "learning" is distorted. The extent of the distortion depends on the degree of disorder of the data. Improper sequence is considerably easier to correct than is data that lacks comparability. The only way to insure comparability of data is to make an exhaustive investigation of the work being performed and the accounting system that classifies the attributable costs. The purpose here is to make certain that (1) significant changes in job content do not go unnoticed and (2) that all assignable costs associated with the work are properly collected. Continuing comparability dictates periodic checks of the work being performed to detect job content changes and the recording of costs.

Knowledge of changes in job content means that collected data must be adjusted in order to be usable as the basis of constructing learning curves. The best method for insuring comparability where job content changes are involved is to establish separate cost accounts

for the changed work as soon as the change is effective. This is not always possible therefore, the method for normalizing data will vary depending on particular circumstances. Section C of Chapter III explains the method that was used to normalize the different weight factors encountered in this study. There is no one way to accomplish this rather difficult task, nor is any method used perfect in its solution.

Having obtained chronology and comparability of the data and having plotted the data, the next task is the determination of the curve that best describes the data. If the linearity of the plotted data is near perfect then the curve can be fitted by visual inspection. However, if the resulting scatter diagram is difficult to interpret then the method of least-squares should be used. This statistical method will develop a regression line that is the best fit for the data plotted. The methodology of this technique is explained in Section D of Chapter I.

The above procedures were applied to the data collected from the NAS Alameda for the A4D-2, A4D-2N, and the P2V-7S. The resulting learning curves were as follows:

A4D-2	90%
A4D-2N	92%
P2V-7S	98.7%

Previous experience was determined as the cause of the reduced

"learning" indicated by the increased curves of the A4D-2N and the P2V-7S. The concept of previous experience, as related to learning curves, in a sense can be interpreted as viewing a given curve as a continuation of a previous curve wherein the experience was gained. Viewed in this light, a minimal learning curve incorporating previous experience, such as the P2V-7S, cannot be dismissed as reflecting an industrial effort practically devoid of learning and for which the learning curve theory offers no management assistance. This thought of dismissal would only be valid if there was never a change in the products to be produced or overhauled. The only process that can be thought of that has not changed over the ages, is the laying of bricks and this perpetuation has only occurred as the result of an unusually strong and long existent union. The rapid advances in technology insure that the products involved in Navy production and overhaul programs will be continually changing and therefore the amount of carry-over of experience from one product to the next will vary depending on the extent of product change.

B. CONCLUSIONS

It is reasonable to conclude that learning curves are applicable to Navy aircraft overhauls. As protrayed by the P2V-7S, the theory is even applicable to overhauls that include a high degree of previous experience. This applicability indicates therefore that the static

basis of overhaul cost determinations needs revision. Utilization of engineered performance standards, in the form of weight factors, from period to period in preparing schedules, manpower requirements, etc., appears inefficient because it does not recognize the existence of the "learning" phenomenon. This study proves the existence of this phenomenon consequently effective management dictates that the learning curve, that gives meaning to the phenomenon, be accepted as a consideration in appropriate Navy decision making.

Acceptance of the learning curve as a factor in decision making incorporates the same psychological pressure on workers that any performance standards system includes. Once a control or quantitative objective is imposed upon an organization, there are strong forces created to make the performance fit the objective. In practice, a system that uses static performance standards is defeating the natural "learning" phenomenon. The word natural is used because in any process involving physical and mental effort of workers "learning" is bound to occur. Learning curves recognize this "learning" and interpret it into a meaningful form that can be used by management. Consequently, if allowances for man-hours are obtained from linear extrapolations of a learning curve, two forces are at work to reduce man-hour costs (1) the natural "learning" indicated by the learning curve and (2) the psychological pressure to make performance fit the allowances.

Although this study was restricted to aircraft overhauls, it is a reasonable assumption that the conclusion reached concerning the learning curve's applicability to aircraft overhauls is also applicable to other Navy production and overhaul or rework programs. A study conducted of selected ship building during World War II revealed an average decline of 16 to 22 per cent in the number of man-hours required in each doubling of output in representative yards building Liberty ships, Victory ships, tankers, and standard cargo vessels.[1] Another writer holds that the learning curve is applicable regardless of whether the industry is aircraft, metalworking, textile, or candy making.[2] These are but a few examples that fortify the idea that learning curves can serve an enlightened management responsible for processes that require physical and mental effort on the part of workers.

C. RECOMMENDATIONS

The purpose of this study was to determine if learning curves are applicable to Navy aircraft overhaul programs with the ultimate objective an improvement of management decisions in construction

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[1]Asher, *op. cit.*, p. 5.

[2]F. J. Andross, "The Learning Curve as a Production Tool," *Harvard Business Review*, Vol. 32 No. 1, January-February, 1954, p. 87.

and overhaul programs by utilizing the unique predictive ability of learning curves. Having established the applicability of learning curves, it is now necessary to recommend actions that should be taken in order to obtain the ultimate objective of improved management decision making.

Realizing that this study is but a limited one, much effort will have to be invested in analyzing empirical data in order to arrive at conclusions as to specific learning curves applicable to each overhaul activity and each series of aircraft.

RECOMMENDATION: That BuWeps initiate a program to develop the family of learning curves for the various types of Naval aircraft and overhaul activities; that BuWeps direct each overhaul activity to determine, from empirical data, applicable learning curves for all plane types undergoing overhaul.

In order to successfully utilize developed learning curves, changes will have to be made to performance reporting and evaluating systems and scheduling methods.

RECOMMENDATION: That BuWeps conduct a study to define the revisions that would be necessary in budgeting, scheduling, reporting and performance evaluation to incorporate the learning curve theory in aircraft overhaul programs.

To facilitate future analyses of cost data, it is most advisable

to effect changes in the cost accounting system so as to obtain refined data for use in learning curve computations.

RECOMMENDATION: That BuWeps modify the cost accounting system at overhaul activities to the extent necessary to achieve chronology and comparability of basic cost data.

There is no reason to believe that the advantages of the learning curve are restricted to BuWeps' aircraft overhaul program. Indications are that this advanced management technique has applicability to any Navy production or overhaul program.

RECOMMENDATION: That all bureaus engaged in production or overhaul programs, conduct studies to determine the applicability of learning curves to the various programs and where applicability is apparent take necessary steps to incorporate the learning curve theory in decision making processes.

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APPENDIX A

APPENDIX A

The following table represents the data for the A4D-2N. In arriving at the net man-hours, the sum of the service change and weight adjustment man-hours are deducted from the gross man-hours. All units were normalized on the basis of a 1.8 weight factor. Chapter III, Section C, contains an explanation of the method used to normalize the weight factor.

TABLE 5

CUMULATIVE AVERAGE MAN-HOUR DATA FOR A4D-2N

UNIT	DATE COMPLETE	BUREAU NUMBER	WGT. FACTOR	GROSS M/H	SERVICE CH. M/H	WGT. ADJ.	NET M/H	CUMULATIVE AVE. M/H
1	2-21-61	145062	1.8	1873	273	000	1600	1600
2	3-07-61	145064	2.3	2244	312	370	1562	1581
3	3-31-61	145066	2.3	2533	601	370	1562	1574
4	4-27-61	145068	1.8	1572	453	000	1119	1460
5	6-07-61	145084	1.8	1693	174	000	1519	1471
6	6-13-61	145077	1.8	1638	196	000	1442	1465
7	6-13-61	145096	1.8	1688	601	000	1087	1411
8	6-20-61	145100	1.8	1653	134	000	1519	1424
9	6-26-61	145085	1.8	1839	415	000	1424	1424
10	6-20-61	145103	1.8	1688	422	000	1266	1408
11	6-26-61	145109	1.8	1764	823	000	941	1365
12	6-26-61	145088	1.8	1820	422	000	1398	1367
13	6-28-61	145090	1.8	1896	439	000	1457	1373
14	6-30-61	145111	1.8	1983	781	000	1202	1360
15	7-11-61	145091	2.6	2172	416	592	1164	1346
16	7-18-61	145094	2.7	2030	342	666	1022	1325
17	7-25-61	145101	2.5	2050	357	518	1175	1316
18	7-27-61	145092	2.6	2224	412	592	1220	1310
19	7-27-61	145065	2.4	2244	357	444	1443	1317
20	8-18-61	145093	2.6	1965	251	592	1122	1307
21	8-24-61	145118	2.5	2077	195	518	1364	1309
22	8-28-61	145127	2.4	2042	216	444	1382	1312

UNIT	DATE COMPLETE	BUREAU NUMBER	WGT. FACTOR	GROSS M/H	SERVICE CH.M/H	WGT. ADJ.	NET M/H	CUMULATIVE AVE.M/H
23	8-31-61	145108	2.5	1841	184	518	1139	1304
24	9-06-61	145095	2.5	1952	198	518	1236	1301
25	9-12-61	145110	2.5	1892	208	518	1166	1295
26	9-14-61	145119	2.5	1773	186	518	1061	1286
27	9-15-61	145115	2.5	1794	226	518	1050	1277
28	9-22-61	145125	2.6	1866	185	592	1089	1270
29	9-28-61	145074	2.6	2058	78	592	1388	1274
30	9-28-61	147669	2.5	1787	205	518	1064	1267
31	10-05-61	147715	2.5	1897	193	518	1186	1264
32	10-05-61	147671	2.5	1820	261	518	1041	1257
33	10-10-61	147673	2.5	1794	233	518	1043	1250
34	10-12-61	145102	2.5	1720	465	518	737	1235
35	10-15-61	147674	2.5	1976	316	518	1142	1232
36	10-21-61	147701	2.5	1839	222	518	1099	1228
37	11-03-61	145123	2.5	2216	284	518	1414	1233
38	11-06-61	147711	2.5	2378	608	518	1252	1233
39	11-06-61	147713	2.5	1926	254	518	1154	1230
40	11-18-61	147749	2.5	1833	236	518	1079	1226
41	11-27-61	147783	2.5	1625	40	518	1067	1222
42	12-04-61	147752	2.5	1780	251	518	1011	1217
43	12-07-61	147788	2.5	1775	40	518	1217	1217
44	12-08-61	147794	2.5	1736	45	518	1173	1216
45	12-11-61	147802	2.5	1457	45	518	894	1209
46	12-12-61	147727	2.5	1714	229	518	967	1204
47	12-12-61	147759	2.5	1788	218	518	1052	1200
48	12-26-61	147755	2.5	1732	236	518	978	1196
49	12-26-61	147816	2.2	1647	60	296	1291	1197
50	12-27-61	147793	2.5	1615	60	518	1037	1194
51	12-27-61	147706	2.9	2014	224	824	966	1190